

Low-Intensity Magnetic Fields Alter Operant Behavior in Rats

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The present study demonstrates that operant behavior is affected by a combination of a 60-Hz magnetic field and a magnetostatic field 2.6×10^{-5} T (about half the geomagnetic field). Rats exposed to this combination for 30 min consistently exhibited changes in the rate and pattern of responding during the differential reinforcement of low rate (DRL) component of a multiple fixed ratio (FR) DRL reinforcement schedule. By contrast, there were no measurable changes following exposure to the static field alone or to the oscillating field alone, even with a 10-fold increase in intensity (5×10^{-5} to 5×10^{-4} T_{rms}). A cyclotron resonance mechanism has been suggested as a possible explanation for the observation that weak static magnetic fields modify the response of in vitro brain tissue to low-frequency magnetic fields. The choice of static field intensity B_0 and frequency ν in the present study follows from the cyclotron resonance condition $\nu = (1/2\pi)(q/m)B_0$, for singly charged lithium, an element in extensive use in the clinical treatment of affective disorders in humans. The present research is consistent with a cellular cyclotron resonance mechanism and tends to imply a functional dependence of behavior on the geomagnetic field.

Key words: 60 Hz, cyclotron resonance, timing discrimination, multiple schedule

INTRODUCTION

It has been reported that weak magnetostatic fields, similar in magnitude to that of the geomagnetic field, modify the response of organisms to low-frequency magnetic fields. Using a well-established experimental protocol [Bawin and Adey, 1976; Blackman et al, 1982], Blackman et al [1985] found that certain combinations of low-frequency (15–45 Hz) magnetic fields and static fields (25–76 μ T) enhance the efflux of calcium ions from in vitro chick brain. A number of these combinations correspond to the cyclotron resonance condition on free, circulating ions [Liboff, 1985a]. Liboff [1985b] indicated that the intrinsic helical structure of the protein subunits that form transmembrane channels represents a particularly appropriate geometry in which to obtain cyclotron resonance. If ions under transport are constrained to paths that tend periodically to encircle the local magnetic field, the motion of these ions will be characterized by a set of allowed frequencies (eigenfrequencies). In principle, the application of an external electromagnetic field tuned to a given eigenfrequency

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should excite a corresponding ionic species in channels that are properly aligned such that the ionic motion is reinforced. The cyclotron resonance frequencies are given by the expression

$$\nu = \frac{1}{2\pi} (q/m) B_0,$$

where (q/m) is the ionic charge to mass ratio and B_0 is the local magnetostatic field.

The present study was undertaken to determine if selected ionic resonant frequencies, as determined by equation 1, can alter behavioral responses *in vivo*. A confirmation of this prediction could strengthen the likelihood of ionic cyclotron resonance occurring in cells. It would also point toward a unique means of correlating behavior with chemical function. Finally, an alteration in behavior would provide evidence that a low-intensity static field of the order of the earth's magnetic field can modify the behavior of animals simultaneously exposed to an alternating field.

The various levels of magnetic field that could be experimentally investigated were constrained by programmatic requirements to study only 60-Hz frequencies. Given the experimental equipment available, the condition on frequency and field shown in equation 1 was relatively easy to achieve at 60 Hz for the case of lithium. Accordingly, rats performing on several schedules of reinforcement were exposed to the combination of ν and B_0 that corresponded to the charge to mass ratio for lithium ions.

METHODS

The subjects were five male Long-Evans hooded rats maintained over the course of this study at 80% of their free-feeding weight of approximately 340 g. The animals were individually housed in a temperature-controlled room with a 12-h light-dark cycle beginning at 0600. Water was available continuously in the home cage. Two chambers were used, a test chamber and an exposure chamber. The test chamber, enclosed in a ventilated, sound-attenuated housing, contained a small response lever mounted on one wall, two lights above the lever, a house light, a speaker, and a hopper connected by a short tube to a feeder that could dispense 45-mg food pellets. There were no constraints on the rats within the test chamber. The animals were trained on a multiple fixed ratio (FR) differential reinforcement of low rate (DRL) reinforcement schedule [Ferster and Skinner, 1957] that required responding on the response lever to produce food pellets. A multiple schedule is a combination of several schedules of reinforcement, each of which is accompanied by a characteristic stimulus. The multiple schedule was such that when a red light above the lever was illuminated and a tone was present, an FR or counting schedule was in effect. On this schedule a rat was required to press the lever 30 times (FR 30) to produce a pellet. An FR schedule generates a rather high and constant rate of responding. When a green light above the lever was illuminated and no tone was present, a spaced-responding or DRL schedule was in effect. On the DRL schedule a pellet was produced by a response on the lever that followed a preceding lever response by at least 18 s (DRL 18). A limited-hold contingency was added to the DRL such that a response could not produce a pellet if it followed a preceding response by more than

24 s. The DRL schedule generally produces a low and steady response rate, with the highest frequency of interresponse times distributed around the DRL value. The FR and DRL schedules were alternated unsystematically with each other during a session, and each schedule was in effect for 3 min at a time. A 30-s time-out period, during which all stimuli in the chamber were off, separated the termination of one schedule and the beginning of the next. A response on the lever during the time-out extended the period of 30 s. Sessions lasted for 1 h and were conducted 5 days per week. Scheduling and data recording were accomplished by a computer control system. Prior to instituting any electromagnetic exposure regimen, several months of daily sessions on the multiple FR DRL schedule established individually reliable rates and patterns of responding for the five subjects.

During exposures the rats were constrained by means of Plexiglas housing located at the midpoint of an array of two sets of coils at right angles to one another (Fig. 1). The inside height of the enclosure was 5.3 cm. The inner set of coils generated a 60-Hz magnetic field directed horizontally along each rat's long axis. Concurrently, the animals could be exposed to a static vertical magnetic field produced by the outer set of Helmholtz coils. Over the course of many weeks, the rats were exposed, using these arrays, for 30 min at a time to low-level static and periodic fields immediately preceding a 1 h test session. Four different magnetic field exposure regimens were used: 1) The rats were given sham (SHM) exposures, with no current applied to either set of coils. In this case the field in the exposure chamber was merely the total earth's field intensity, 4.04×10^{-5} T. The components of the local geomagnetic field were measured with a fluxgate magnetometer provided by the Magnetics Laboratory, National Bureau of Standards, Gaithersburg, MD. The 60-Hz background was measured at $< 1 \times 10^{-7}$ T_{rms}. 2) The rats were exposed to an applied oscillatory 60-Hz field vector (OSC) directed along each rat's long axis. The field

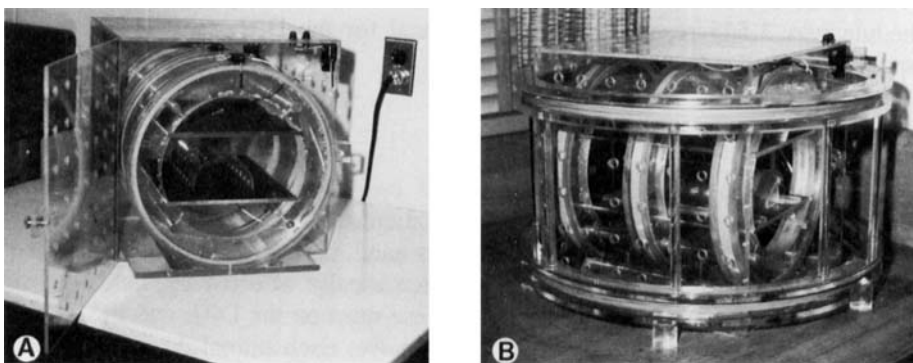


Fig. 1. Photographs of the exposure system. A) The inner set of three coils was used to apply a horizontal oscillating magnetic field parallel to the rat's long axis. The hemicylindrical plastic constraint is shown in the center. The two horizontal aluminum electrodes were for application of vertical E fields (not used in the present work). Note that the coils are in a threefold configuration, 2N, N, 2N, with N = 24 turns. Coil diameters are 31.0 cm, and separation of one coil from the next is 13.3 cm. The midfield is $B = 2.67 I \times 10^{-4}$ T. B) The outer set of two coils was used in combination with the inner set, as shown. The outer set was used to apply a vertical magnetostatic field opposite in direction to the vertical component of the local geomagnetic field and perpendicular to the linearly polarized 60-Hz field. These coils are close to a Helmholtz configuration. The mean coil diameter is 51.75 cm, and the coil separation is 25.1 cm. There are 70 turns in each coil. The midfield is $B = 2.47 I \times 10^{-4}$ T.

intensity was normally set to $5 \times 10^{-5} T_{\text{rms}}$; the earth's field was unchanged. 3) With no applied 60-Hz field, rats were exposed only to a changed static field (STA). The vertical component of the earth's field was such that the total earth's field was reduced from $4.04 \times 10^{-5} T$ to $2.61 \times 10^{-5} T$. 4) The 60-Hz field was combined with the static field $2.61 \times 10^{-5} T$ (COM).

The parameters in regimen 4 are consistent with the cyclotron resonance condition for singly ionized lithium. If one substitutes into equation 1 the charge to mass ratio (q/m) = 1.39×10^7 coul/kg and the frequency $\nu = 60$ Hz, the magnetic field that results is $B_0 = 0.271 \times 10^{-4} T$ (0.271 gauss). The measured local earth's field was $0.404 \times 10^{-4} T$, with the vertical component $0.345 \times 10^{-4} T$. The outer set of coils was used to generate a vertical component equal to $0.188 \times 10^{-4} T$, directed oppositely to the earth's vertical component. The local vertical component was thereby reduced to $0.157 \times 10^{-4} T$, and the total local field was reduced to $B_0 = [(.157)^2 + (.209)^2]^{1/2} \times 10^{-4} T = 0.271 \times 10^{-4} T$. Because of the limited fine adjustment on the DC power supply used as a current source for the outer coils, the best match to this value that could be achieved was $0.261 \times 10^{-4} T$.

Each animal was exposed to a particular regimen no more than twice per week (usually Tuesday and Friday). Five replications of each condition were obtained over successive weeks. Baseline sessions preceded and followed the exposures. Before the effects of any magnetic exposures were studied, the animals were adapted over a number of weeks to the Plexiglas exposure housing by being placed in it for 30 min before a session until baseline performance with and without the housing was the same. Subsequently, during the course of the study, the animals were again placed in the exposure chamber for 30 min as a sham control (as in regimen 1 above). The behavioral data were evaluated by comparing the same animal's response rate (responses per second) and pattern of responding on the FR and DRL schedules during field exposure sessions with its performance during preceding baseline sessions. Averaged across all animals, the overall mean baseline response rate for the FR schedule was 3.545 responses per second, and for the DRL schedule it was .055 responses per second.

RESULTS

Exposures to the combined static and oscillating fields (regimen 4 above) consistently produced a systematic modification in both the rate and pattern of responding on the DRL schedule. On the other hand, performance on the FR schedule or during the time-out period was not systematically affected by field exposure. Figure 2 shows the relative changes in response rates on the DRL and FR schedules for each of the four exposure conditions listed above. Each animal showed a consistent and reproducible increase in the rate of responding on the DRL schedule as a result of exposure to the COM, or "resonant" combination. Although the OSC and the STA exposures each represents part of the combined exposure, neither part alone resulted in any consistent change in DRL response rate.

The changes that occurred in the temporal pattern of behavior for one animal as a function of magnetic field exposure are shown in Figure 3. These data, representative of the DRL session data for each animal, show that under baseline conditions the largest number of responses followed a preceding response by about 16 to 20 s, indicating a rather precise temporal discrimination. However, following exposure to

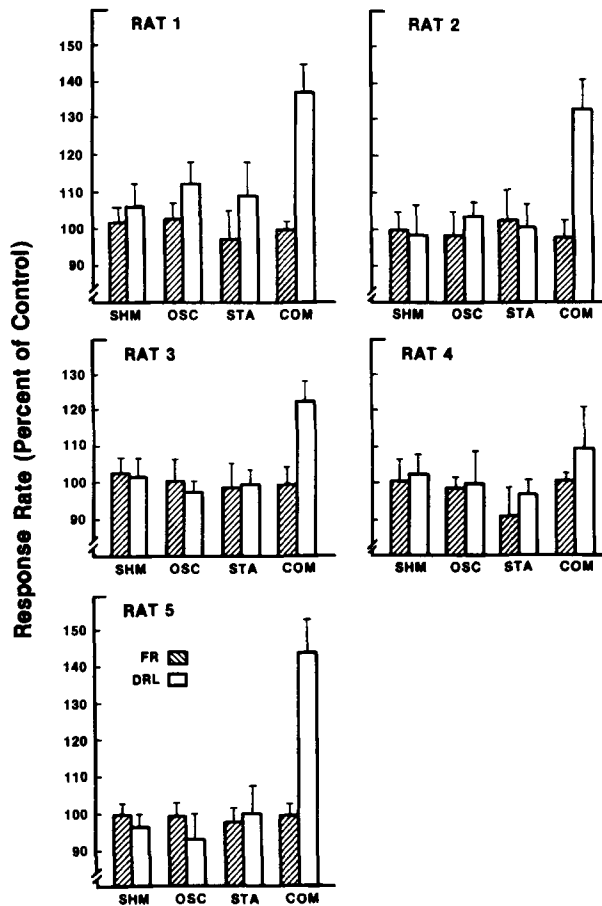


Fig. 2. Changes in rates of responding (expressed as percentage of the mean of all baseline control sessions preceding field exposure sessions) are shown for both the DRL and FR schedules for the four exposure conditions. SHM, sham exposure; OSC, exposure to the 60-Hz field alone; STA, exposure to a revised local field; and COM, exposure to the combined, "resonant" fields. In each case the value plotted is the mean of five sessions. Vertical lines indicate standard deviations.

the COM field condition, the response distribution is flattened and is shifted toward shorter interresponse times. This shift reflects the increased response rate shown in Figure 2; the flattening of the distribution may indicate a reduction in temporal discrimination.

Figure 4 shows two cumulative-response records for a session following COM magnetic field exposure (A) and a baseline session (B) for one animal. Higher rates of responding can be seen during much of the DRL segments for the session after COM field exposure. The higher response rates that occur during the field session were also associated with a marked decline in food pellet frequency (indicated by a reduction in the number of pips during the DRL segments because of the occurrence of the large number of responses that were not properly spaced). The behavioral changes that did occur on DRL schedules were transitory. Performance returned to control levels within 24 h. Comparison of the two cumulative records shows that

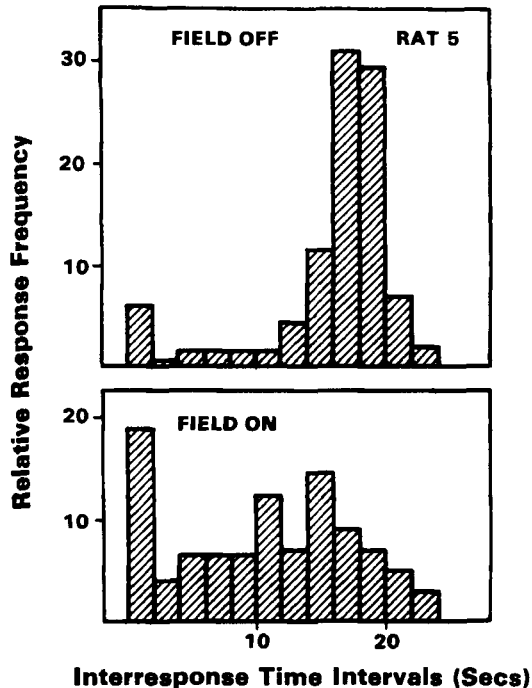


Fig. 3. Relative frequency distribution of time intervals between successive lever responses during DRL segments of one animal for a baseline control session (field off) and a magnetic field exposure session (field on). Each interresponse time interval is 2 s wide, and the last interval contains all responses that followed a preceding response by 22 s or longer.

there were no systematic differences in the FR schedule performance as a result of the magnetic field exposure.

As pointed out above in connection with Figure 2, no changes in behavior on the multiple FR DRL schedule were observed when the animals were exposed to the 60-Hz magnetic field alone (OSC). Indeed, systematic behavioral effects were never produced by the 60-Hz field alone for a wide range of field intensities, from $5 \times 10^{-5} T_{\text{rms}}$ to $5 \times 10^{-4} T_{\text{rms}}$. Similarly, systematic disturbances of behavior were never observed when the animals were exposed to the altered earth's field alone (STA). The observed changes in behavior occurred only following exposure to the combined static and oscillating fields.

DISCUSSION

There are a number of distinct conclusions to be drawn from the present study. First, behavioral changes occur in rats that are exposed to weak, low-frequency magnetic fields. These changes appear to be reversible, lasting for at least 1 h following exposure but not 24 h. Second, the field configuration required to effect these changes consists of a combination of static and oscillating fields, an observation strongly suggesting a resonance phenomenon. The specific combination of field and frequency employed, dictated by the experimental equipment available that concentrated on 60-Hz frequencies, is consistent with the cyclotron resonance condition for

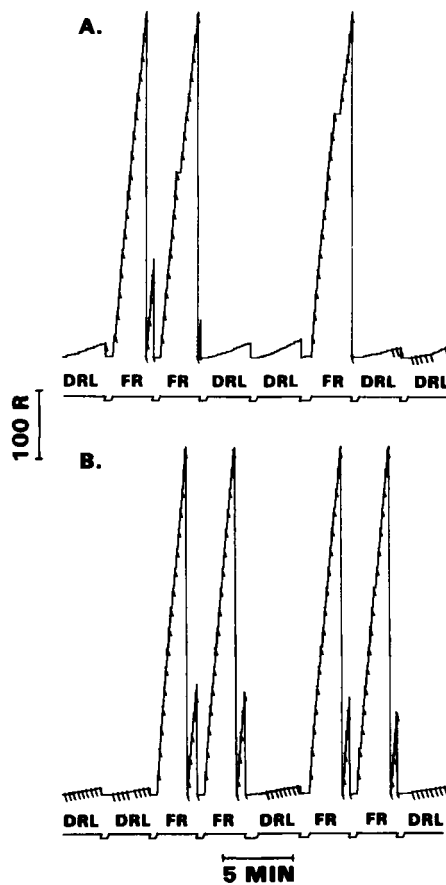


Fig. 4. Cumulative response records of one animal for portions of a magnetic field exposure session (A) and a baseline session (B). Each recording response stepped the recording pen upward. Pips indicate delivery of a food pellet. The bottom pen was down during the time-out periods that separated successive FR and DRL schedules.

unhydrated lithium ions. The facts that the behavioral changes occurred only for combined fields and that the particular combination enjoys a close correspondence to the singly charged lithium ion constitute a fairly strong indication that a mechanism akin to cyclotron resonance may be involved in the behavioral changes. Furthermore, it is well established [Kandel and Schwartz, 1981] that lithium plays a role in brain biochemistry. When administered as a carbonate, it can be used to treat bipolar affective disorders in humans. Presumably, enhanced lithium concentration increases the sensitivity of serotonin receptors and α -adrenergic receptors. The manner in which lithium affects operant behavior in rats is not clear, although some lithium-dependent behavioral changes have been reported [Smith, 1977]. It is conceivable that the results obtained in the present work may be related to the resonant efflux of lithium ions from cells in rat brains.

It is instructive to compare present results with earlier studies on electromagnetically induced behavioral effects, particularly in the low-intensity domain. Microwave (2.45 GHz) exposures at intensities as low as 5 mW/cm² have been related [Thomas

et al, 1975] to changes in the temporal patterning of behavior of rats trained on multiple reinforcement schedules. More recent work [Thomas et al, 1982] has indicated that such changes are more pronounced under pulsed-wave (rep rate 500 Hz) than under CW exposure. The study of behavioral effects at lower frequencies has received surprisingly little attention. Gavalas et al [1970] and Gavalas-Medici and Day-Magdaleno [1976] observed a reduction in interresponse times in monkeys performing on DRL schedules following exposure to weak *electric* fields at frequencies in the range 7 to 75 Hz. Changes in locomotor activity and vocalizations in mice have been correlated [Smith and Justesen, 1977] with low-level 60-Hz fields. A series of experiments concerned with operant behaviors reported by deLorge (1972, 1973a,b, 1974) and deLorge and Marr [1974], however, failed to detect any reliable behavioral changes as a result of low-frequency electromagnetic fields. These investigators reported data from rhesus monkeys, pigeons, and rats exposed to fields from 7 to 75 Hz with a range of magnetic and electrical field densities. The behavioral baselines investigated included tests of field effects on ability to detect fields; effects on reaction time, matching-to-sample, and temporal discrimination performances; and effects on fixed-interval and concurrent chain reinforcement schedules. The investigators reported no detectable change in behavior under any of the conditions studied. There is the possibility that these earlier measurements for the most part represented the average of unchanged responses with occasional resonant responses. This would have resulted in the overall behavioral response being changed marginally or not at all. In principle, one need not restrict the resonance possibility to merely lithium.

There are combinations of fields that theoretically correspond to all the physiologically significant ions (Na^+ , K^+ , Cl^- , Ca^{2+} , Mg^{2+} —), different states of hydration, higher harmonics, and so forth. It would be reasonable to design future experiments in electromagnetically induced changes in behavior around such biochemical parameters rather than merely levels of intensity.

Quite apart from the question of resonance, the present results tend to suggest a functional dependence of behavior on the geomagnetic field. This field varies from 0.25×10^{-4} to 0.70×10^{-4} T over the earth's surface. There is a good likelihood of occasional human exposure to the particular combination of a 60-Hz field and a 0.26×10^{-4} T magnetostatic field, especially at low geomagnetic latitudes. Further, if indeed a cyclotron resonance mechanism is the explanation for what was observed in the present study, there will be other critical combinations of the geomagnetic field with the 60-Hz background.

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Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, DHEW, Pb. No. (NIH) 78-23.

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